HEAT TRANSFER

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Heat Transfer is the movement of heat from one body to another by means of conduction, convection or radiation and both.

Modes of HEAT TRANSFER:

(1) **Conduction** - is a mode of heat transfer in which heat is transferred by molecular interaction through bodies in contact. In solids, particularly metals, conduction is due to the drift of free electrons and photons and phonon vibration. At low temperatures, phonon vibration, the vibration of crystalline structure is the primary mechanism for conduction, and at high temperature electron drift is the primary mechanism. Regardless of the mechanism, energy is transfer from one atom or molecule to another, resulting in a flow of energy within the medium or substance. The Law for conduction of heat transfer was known as the Fourier's Law.

Convection - is a mode of heat transfer in which heat is transferred due to mixing and motion of particles of a substance. It can be a heat transfer between a solid surface and a fluid. This is mixed mode, in that at the solid-fluid interface heat is transfer by conduction, molecular collisions between the solid and fluid molecules. As a result of this collision the temperature will change, the density varies and the bulk fluid occurs.

TYPICAL UNIT CONVECTIVE COEFFICIENT VALUES	
Mode	h_C (W/m^2.k)
Free convection, air	5 to 25
Forced convection, air	10 to 200
Free convection, water	20 t0 100
Forced convection, water	50 to 10,000

2.1 **Free Convection** - the substance moves because of the decrease in its density which is caused by increase in temperature.

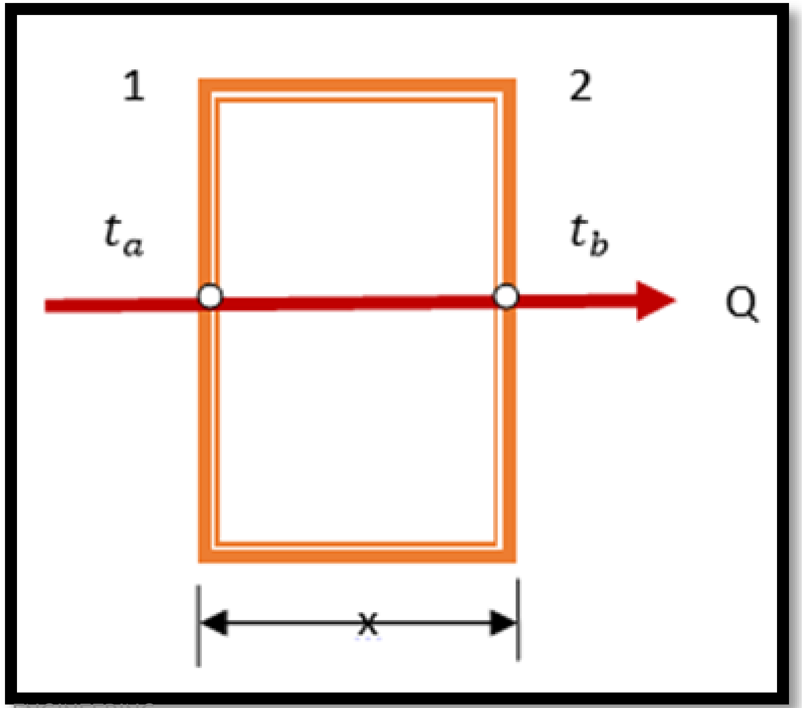
2.2 **Forced Convection** - the substance moves because of the application of mechanical power such as that of a fans or mechanical blowers.

Radiation - is a mode of heat transfer in which heat is transferred between bodies by energy propagating electromagnetic waves. It is also a thermal energy flow via electromagnetic waves, between two bodies separated by a distance. The Law for radiative heat transfer was discovered by J. Stefan and L. Boltzmann.

Conduction through plane walls:

For a steady state unidirectional flow of heat through a homogenous plane wall, Fourier's equation gives the heat by conduction as:

$$Q = \frac{kA(t_a - t_b)}{x},$$

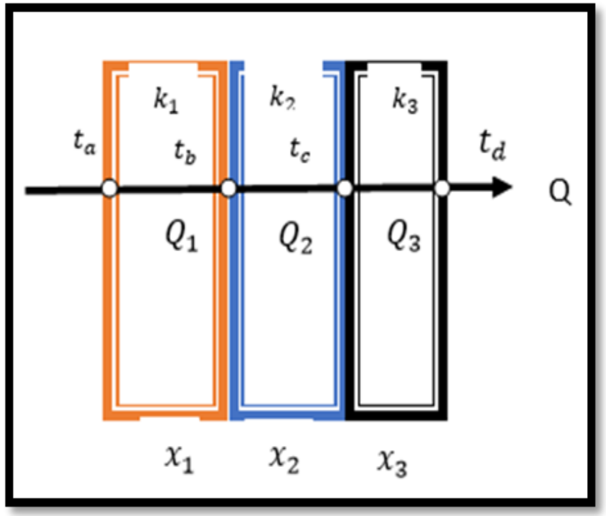


Where:

$$\mathrm{Q = Heat\ Transmitted, W}$$
$$\mathrm{A = Area\ of\ Heat\ Transfer, m^2}$$
$$\mathrm{t_a = Surface\ Temperature\ hot\ side}$$
$$\mathrm{t_b = Surface\ Temperature\ hot\ side\ cold\ side}$$
$$\mathrm{x = thickness\ of\ the\ wall, m}$$
$$\mathrm{k = thermal\ conductivity, \frac{W}{m - deg\ C}}$$

Conduction through composite plane walls:

For a composite wall shown in the figure, if the heat flows in series first trough one slab and then another, Fourier's equation can be applied as:



$$Q_1 = \frac{k_1 A(t_a - t_b)}{x_1},$$

$$Q_2 = \frac{k_2 A(t_b - t_c)}{x_2},$$

$$Q_3 = \frac{k_3 A(t_c - t_d)}{x_3},$$

$$Q = \frac{A\Delta t}{R_T} = \frac{A(t_a - t_d)}{\frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3}}$$

Where:

R_T = Overall resistance

$Q = Q_1 = Q_2 = Q_3$ for steady state heat transfer

k_1 = Thermal conductivity of the first layer of the wall

k_2 = Thermal conductivity of the second layer of the wall

k_3 = Thermal conductivity of the third layer of the wall

A = is a heat transfer area common to both walls

$$Q = h_i A(t_i - t_a)$$
$$Q = h_o A(t_d - t_o)$$

$$Q_1 = \frac{k_1 A(t_a - t_b)}{x_1},$$

$$Q_2 = \frac{k_2 A(t_b - t_c)}{x_2},$$

$$Q_3 = \frac{k_3 A(t_c - t_d)}{x_3},$$

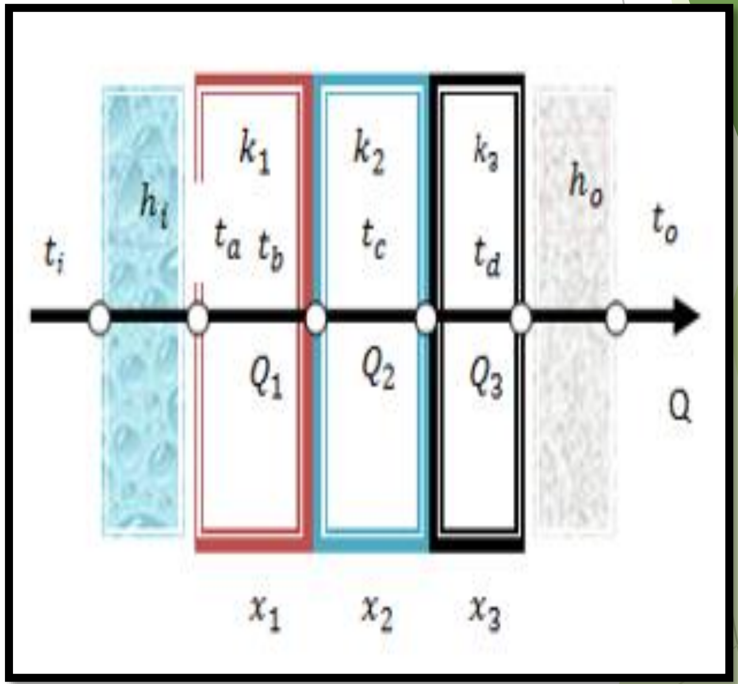
$$Q = \frac{A(t_i - t_o)}{\frac{1}{h_i} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \frac{1}{h_o}}$$

$$Q = \frac{A\Delta t}{R_T}$$

$$Q = UA\Delta T$$

$$A = \pi r^2$$

$$U = \frac{1}{R_T} = \frac{1}{\frac{1}{h_i} + \frac{x_1}{k_1} + \frac{x_2}{k_2} + \frac{x_3}{k_3} + \frac{1}{h_o}}$$



Where:

$$h_1 = \text{surface conductance}, \frac{\text{W}}{\text{m}^2 - \deg \text{C}} \ \text{hot}$$

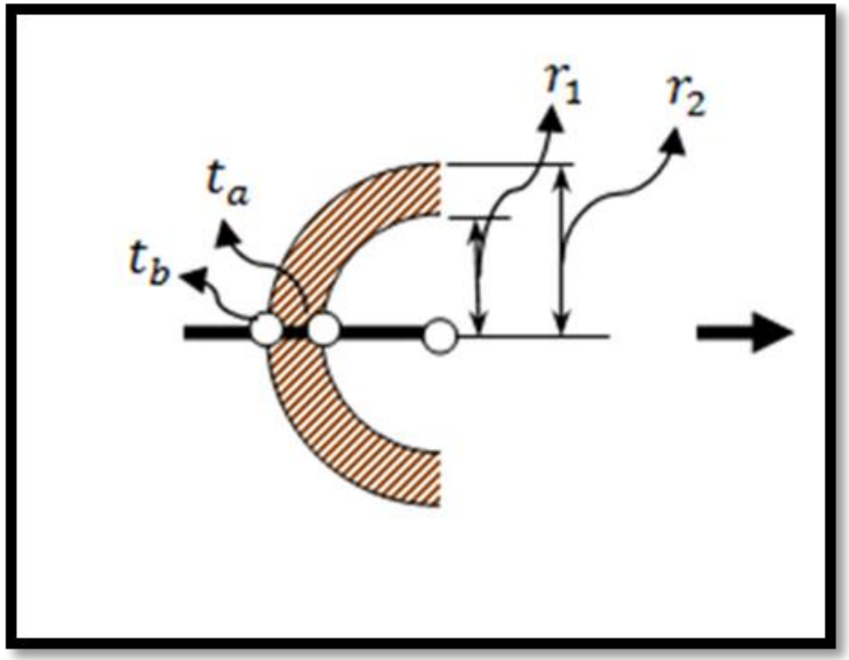
$$h_2 = \text{surface conductance}, \frac{\text{W}}{\text{m}^2 - \deg \text{C}} \ \text{cold}$$

R_T = Overall resistance

U = Overall conductance or overall coefficient of heat transfer

Conduction through pipe:

In conduction through pipe assume that heat flows in the radial direction from inside to outside surface. Fourier equation gives the heat loss as:



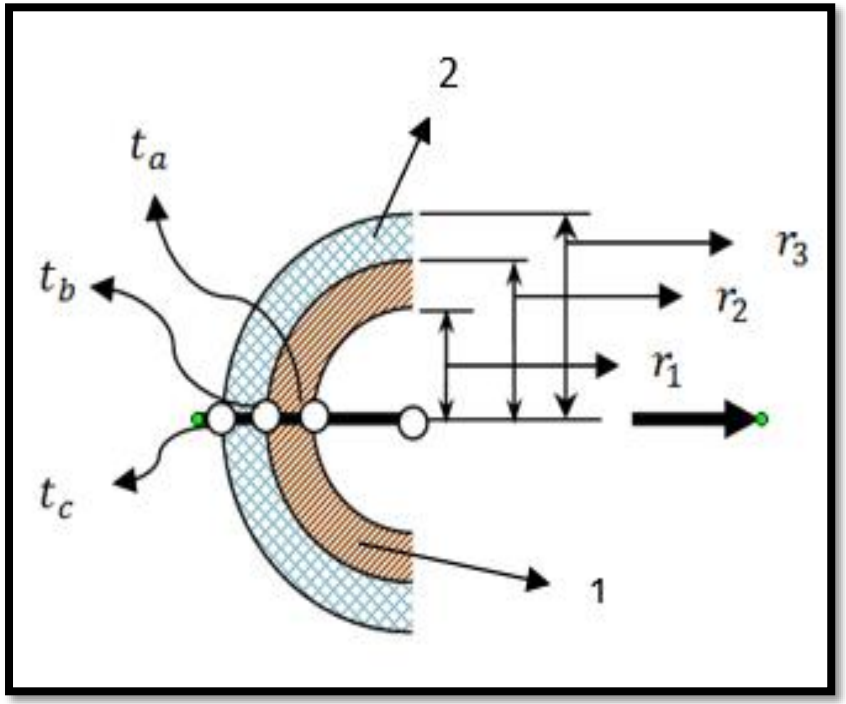
$$Q = \frac{2\pi k L(t_a - t_b)}{\ln\frac{r_2}{r_1}},$$

$$or\ \frac{r_2}{r_1} = \frac{d_2}{d_1}$$

L = length of the pipe

$Q = Q_1 = Q_2 = Q_3$ for steady state heat transfer

Conduction through composite pipe:



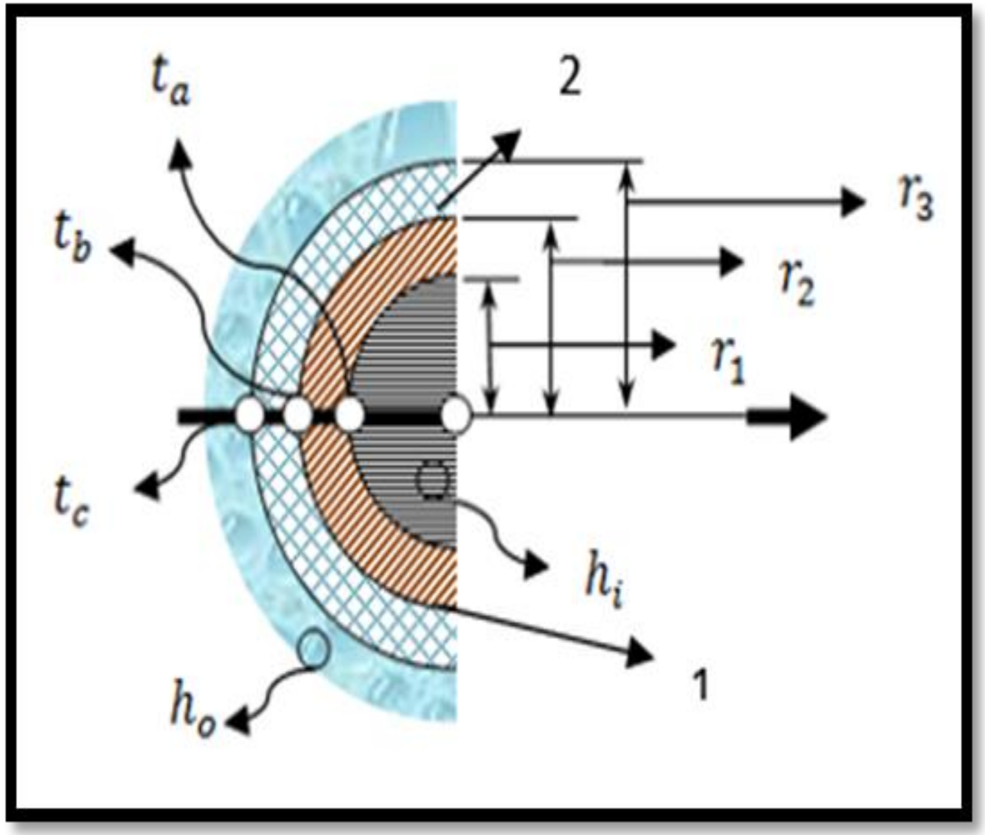
$$Q_1 = \frac{2\pi k_1 L(t_a - t_b)}{\ln\frac{r_2}{r_1}}$$

$$Q_2 = \frac{2\pi k_2 L(t_b - t_c)}{\ln\frac{r_3}{r_2}}$$

$$Q = \frac{\Delta t}{R_T} = \frac{2\pi L(t_a - t_c)}{\frac{\ln\frac{r_2}{r_1}}{k_1} + \frac{\ln\frac{r_3}{r_2}}{k_2}}$$

$L = length\ of\ the\ pipe$

Conduction of fluid to fluid through composite pipe:



$$Q = h_iA_i(t_i - t_a)$$
$$Q = h_oA_o(t_c - t_o)$$
$$Q_1 = \frac{2k_1L(t_a - t_b)}{\ln\frac{r_2}{r_1}}$$
$$Q_2 = \frac{2k_2L(t_b - t_c)}{\ln\frac{r_3}{r_2}}$$

$$Q = \frac{\Delta t}{R_T}$$

$$= \frac{(t_i - t_o)}{\frac{1}{h_iA_i} + \frac{\ln\frac{r_2}{r_1}}{2\pi k_1 L} + \frac{\ln\frac{r_3}{r_2}}{\cdots} + \frac{1}{\cdots}}$$

$$eat\ Transfer\ in\ terms\ of\ overall\ conductance:$$

$$Q = U_i A_i \Delta t\ mean,$$

$$U_i = overall\ conductancebased\ on\ inside\ area$$

$$Q = U_o A_o \Delta t\ mean,$$

$$U_o = \ overall\ conductancebased\ on\ outside\ area$$

Where:

$Q = Q_1 = Q_2 = Q_3$ for steady state heat transfer

$$h_i = surface\ conductance\ on\ inside$$

$$h_o = surface\ conductance\ on\ outside$$

$$A_i = inside\ surface\ area, 2\pi r_1 L$$

$$A_o = outside\ surface\ area, 2\pi r_2 L$$

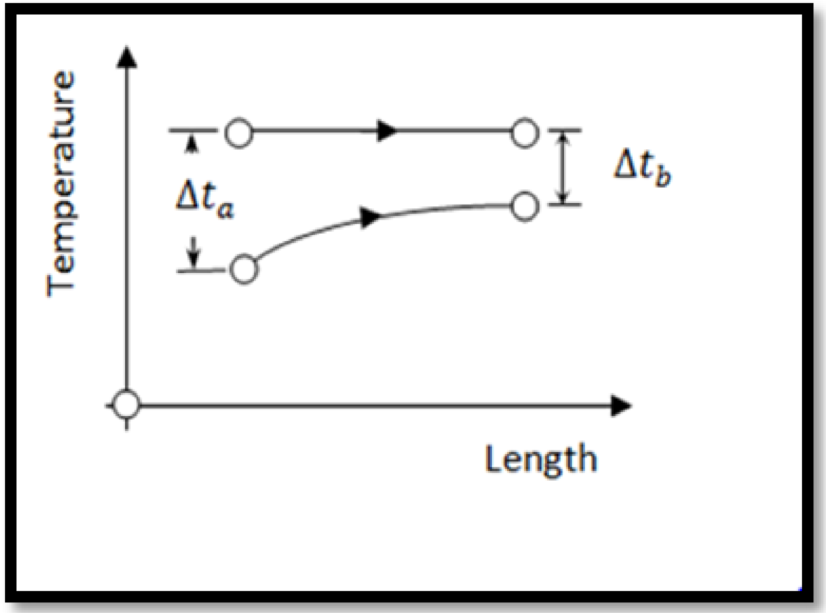
Heat Exchangers

Heat exchanger is any device which affects the transfer of heat from one another to another.
Examples of heat exchanger are:

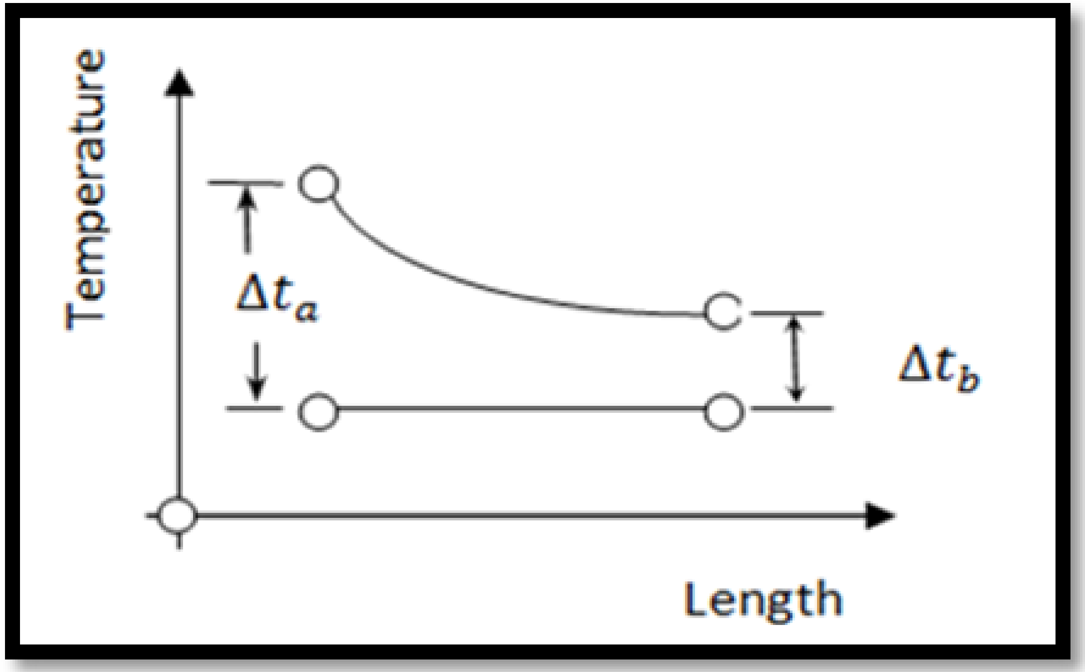
- Water Heater
- Oil Heaters
- Evaporators
- Economizers
- Fluid Heaters and Coolers
- Tube Banks
- Steam condensers
- Steam boilers

Classification of Heat Exchangers

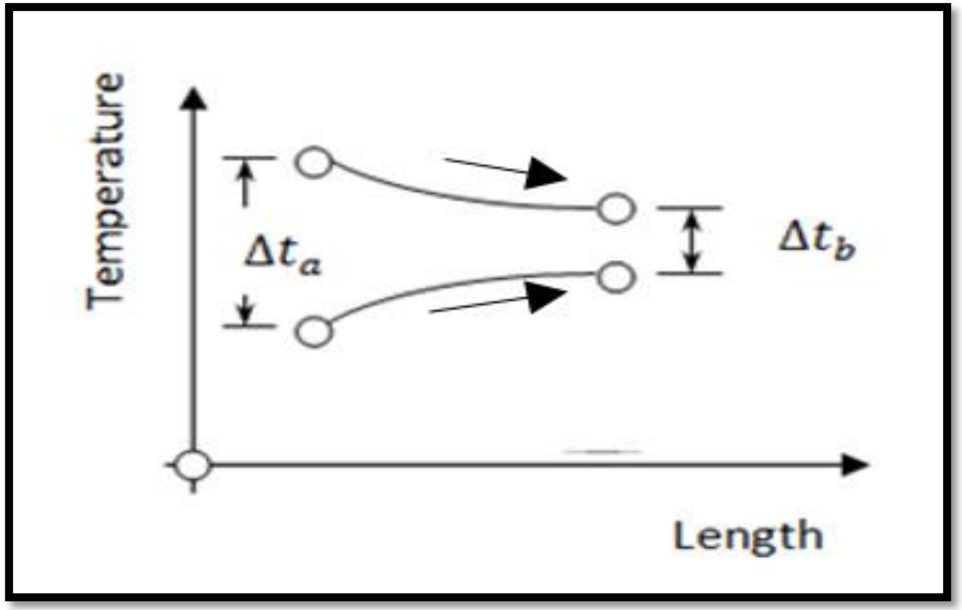
Heat Exchangers wherein a fluid at constant temperature gives up heat to a cooler fluid the temperature of which gradually increases as it flows through the device. The heating fluid can be at rest moving in any direction. An example of this type would be a steam condenser.



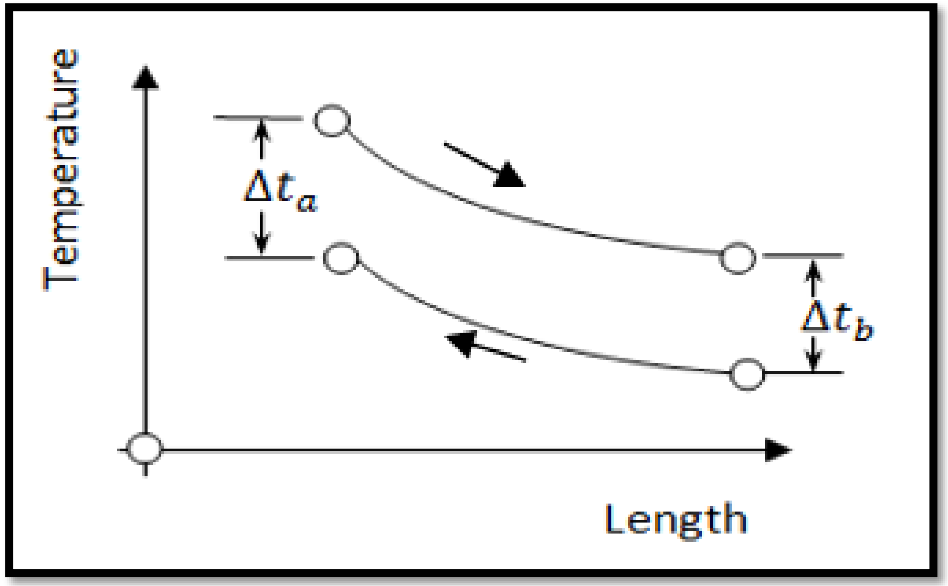
Devices wherein a fluid at constant temperature receives heat from a warmer fluid the temperature of which decreases as it flows through the exchanger. The heated fluid can be at rest or moving in any direction. An example of this type is a steam boiler.



Parallel Flow heat exchangers wherein the fluids flow in the same direction and both them change their temperature .an examples of this are water heater, oil heater and coolers.

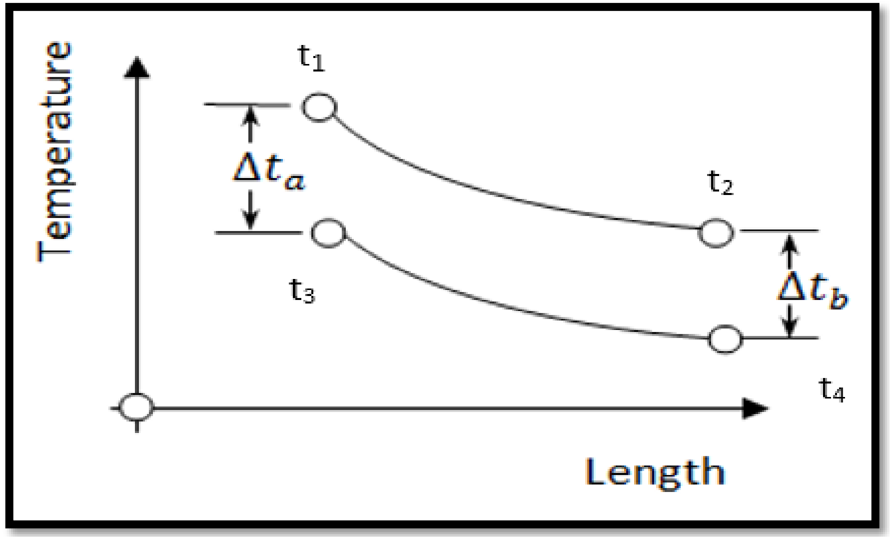


Counter flow heat exchangers wherein the fluids flow in directions opposites to one another. This possibly the most favourable kind of fluid heaters and coolers.



Cross-flow heat exchangers in which one fluid flow at an angle to the second one as the case in tube banks.

Logarithmic Mean Temperature Difference (LMTD)



$$LMTD = \frac{(\Delta t)_{max} - (\Delta t_{min})}{\ln \frac{(\Delta t)_{max}}{(\Delta t)_{min}}}$$

$(\Delta t)_a = t_1 - t_3$

$(\Delta t)_b = t_2 - t_4$

Arithmetic Mean Temperature Difference (AMTD)

$$AMTD = \frac{(\Delta t)_a + (\Delta t_b)}{2}$$

$$Mean\ Temperature\ Differince$$

$$A.\ Parallel\ Flow$$

$$\Delta t_a = t_x - t_1$$

$$\Delta t_b = t_y - t_2$$

$$B.\ Counter\ Flow$$

$$\Delta t_a = t_y - t_1$$

$$\Delta t_b = t_x - t_2$$

CONVECTION

Convection is the mechanism of heat transfer whereby heat energy is transferred by moving fluids.

Most important dimensionless group in the analysis of heat convection.

Reynolds Number, N_{RE}

Reynold's number is a dimensionless number which is significant in the design of a model any system in which the effect of viscosity is important in controlling the velocities or the flow pattern of a fluid; equal to the product of density, of velocity and diameter by the fluid viscosity.

$$N_{RE} = \frac{VD\rho}{\mu_d}$$

Where:

V= velocity, m/sec

D= diameter, m

ρ= density, kg/m^3

μ_d = Absolute or dynamic viscosity, Pa-sec

μ_k = kinematics viscosity, m^2/sec

μ_k = Dynamic viscosity/Density

Prandlt Number, N_{Pr}

Prandlt number is a dimensionless number used in the study of forced and free convection, equal to the dynamic viscosity times the specific heat at constant pressure divided by the thermal conductivity.

$$N_{pr} = \frac{\mu_d C_p}{k}$$

Where:

μ_d = Dynamic viscosity
C_p = Specific heat
k = thermal conductivity

Nusselt Number, N_{Nu}

Nusselt number is a dimensionless number used in the study of forced convection which gives a measure of the ratio of the total heat transfer to conductive heat transfer, and is equal to the heat-transfer coefficient times the diameter divided by the thermal conductivity.

$$N_{Nu} = \frac{hD}{k}$$

Where:

h = heat transfer coefficient

k = thermal conductivity

D = pipe diameter

Grashof Number, N_{GR}

Grashof number is a dimensionless number used in the study of the free convection of a fluid caused by a hot body. It is equal to the product of the fluid coefficient of thermal expansion, the temperature difference between the body and the fluid, the cube of the typical dimension of the body and the square of the fluids density divide by the square of the fluids dynamic viscosity.

$$N_{GR} = \frac{D^3 \rho^2 \beta g \Delta t}{\mu_d^2}$$

Where:

D= diameter

g = constant acceleration due to gravity

$\rho = density$

$\mu_d = viscosity\ of\ the\ fluids$

$\beta = coefficient\ thermal\ expansion$

$\Delta t = temperature\ difference\ between\ the\ surface\ and\ fluid$

Convective Heat Transfer with known specific heat:

$$Q = mC_p\Delta t = mC_p(t_2 - t_1)$$

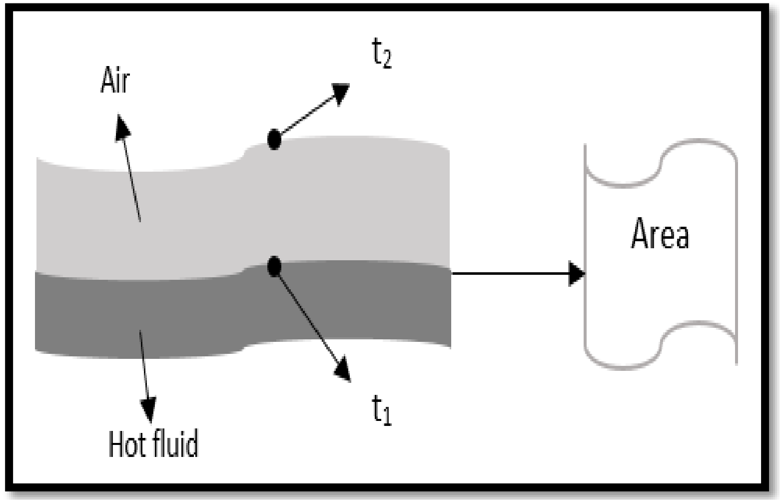
Where:

m= mass flow rate, kg/s

$$C_p = specific\ heat, \frac{J}{kg - °C}$$

$$\Delta t = tempearature\ differince$$

Surface Convection



$$Q = h_c A \Delta t = h_c A(t_1 - t_2)$$

Where:

h_c = surface coefficient associated with convection, W/m²

A = area of heat transfer, m²

t_1 = hot surface temperature, K or °C

t_2 = fluid temperature, K or °C

RADIATION

Radiant heat exchange between two surfaces can be computed from:

$$Q = 20408.4\,X\,10^{-8} Fe(A)[(T_1)^4 - (T_2)^4], \frac{J}{Hr}.$$

Where:

Q=heat transmitted by radiation, J/hr

Fe= emissivity factor, unit less

A= radiating surface area, m^2

T_1= absolute temperature of surface radiating the heat, K

T_2= absolute temperature of surface receiving the heat, K

The Concept of a Perfect Black Body

Perfect Black body is a body that absorbs all electromagnetic radiation. Absorbs all wavelengths such no reflection occurs.

$$a + r + t = 1$$

Where:

a = absorptivity or the fraction of the total energy absorbed

r= reflectivity or the fraction of the total energy reflected

t=transmitted or the fraction of the total energy transmitted through the body

Plank’s Law

All substances emit radiation, the quantity and quality in which depends upon the absolute temperature and the properties of the material, composing the radiating body.

Kirchhoff’s Law

For bodies in thermal equilibrium with their environment, the ratio of the total emissive power to the absorptivity is constant at any temperature.

Stefan Boltzmann Law

The total energy emitted by a black body is proportional to the fourth power to the absolute temperature of the body.

Sample Problems:

Calculate the heat conducted through a 0.2 m thick industrial wall made of fireclay brick. Measurement made during steady-state operation showed that the wall temperatures inside and outside the furnace are 1500 deg K and 1100 deg K respectively. The length of the wall is 1.2m and the height is 1m.

Solutions:

$$Q = \frac{kA(t_1 - t_2)}{x}$$

Thermal conductivity for fireclay brick= $1.7 \frac{W}{m \deg K}$

Area = 1.2 m X 1.0 m= $1.2m^2$

$$Q = \frac{\frac{1.7W}{m \deg K} X\ 1.2\ m^2 (1500\ K - 1000K)}{0.2\ m} = 4080\ W$$

The heat flux, q, is 6000W/m^2 at the surface of an electric heater. The heater temperature is 120 ℃ when it is cooled by air at 70 ℃. what is the average convective heat transfer coefficient, U? what will the heater temperature be if the power reduced so that the q is 2000W/ m^2.

Solutions:

$$U = \frac{Q}{\Delta T} = \frac{6000}{120 - 70} = 120\,\frac{W}{m^2 - ℃}$$

Due Forced convection U=$120\,\frac{W}{m^2 - ℃}$, remains unchanged.

$$\Delta T = T_{heater} - 70℃ = \frac{Q}{U} = \frac{2000\,\frac{W}{m^2}}{120\,\frac{W}{m^2 - ℃}} = 16.67℃$$

$$T_{heater} = 70 + 16.67 = 86.67℃$$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